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AN AGENT-BASED FRAMEWORK FOR SUSTAINABLE PERISHABLE FOOD SUPPLY CHAINS

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ABSTRACT

This study presents an agent-based modeling framework for enhancing the efficiency and sustainability of perishable food supply chains. The framework integrates forward logistics redesign, reverse logistics, and waste valorization into a spatially explicit simulation environment. It is applied to the tomato supply chain in Jordan, restructuring the centralized market configuration into a decentralized closed loop system with collection points, regional hubs, and biogas units. The model simulates transportation flows, agent interactions, and waste return through retailer backhauls. Simulation results show a 31.1 percent reduction in annual transportation distance and cost, and a 35.9 percent decrease in transportation cost per ton. The proposed approach supports cost-effective logistics and a more equitable distribution of transport burden, particularly by shifting a greater share to retailers. Its modular structure, combined with reliance on synthetic data and scenario flexibility, makes it suitable for evaluating strategies in fragmented, resource-constrained supply chains.

1 INTRODUCTION

Perishable Food Supply Chains (PFSCs) are particularly challenging due to the delicate and short-lived nature of their products. Each stage—harvesting, processing, transport, storage, and distribution—must be carefully managed to maintain product quality and safety (Duarte et al. 2024). Poor infrastructure, such as limited cold storage and unreliable transport, exacerbates spoilage and waste (Kumar et al. 2020). Fluctuating consumer demand further causes surpluses or shortages, leading to economic losses and unsold spoilage (Laktena 2023; Luo et al. 2022). These issues are especially pronounced in developing regions, where small farms are dispersed, infrastructure is lacking, and centralized markets dominate. Farmers often bear high transportation costs that may exceed the value of their goods (Kumar et al. 2020).

Globally, one-third of food produced for human consumption—approximately 1.3 billion tons—is lost or wasted annually, amounting to nearly $1 trillion (FAO 2011). About 14% of this loss occurs after harvest and before retail, mainly due to storage, transport, and distribution inefficiencies (FAO 2019). Losses are more severe in developing regions, and the environmental costs are significant. Resources used in producing and transporting wasted food contribute to greenhouse gas emissions, with over 85% of emissions from landfilled food waste occurring during earlier stages (EPA 2023). Food loss and waste are estimated to account for 8–10% of global emissions (UNFCCC 2023), highlighting the urgent need for more efficient and sustainable PFSCs.

Improving PFSC performance often involves redesigning forward logistics networks to address inefficiencies. Recent studies emphasize network flow optimization as a key strategy. Liu et al. (2021) introduced a multi-objective model integrating location, inventory, and routing, enhancing both economic and environmental outcomes. Al-Zubi et al. (2022) demonstrated that in Jordan's citrus sector, the introduction of 52 collection points and two hubs cut transportation costs by 60% and reduced emissions. Pan and Shan (2024) developed a hybrid metaheuristic model to optimize production-location-inventory decisions. Sweis et al. (2024) proposed a top-down methodology to generate synthetic yet realistic data, facilitating accurate PFSC simulation under uncertainty using spatial analysis and coding tools. Bolívar et

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al. (2025) created a linear programming model tailored to Colombian smallholders, optimizing warehouse and product flow decisions with quality considerations.

Addressing end-of-life challenges through reverse logistics (RL) and waste valorization is equally essential. Bottani et al. (2019) used life cycle assessment to evaluate RL scenarios for food waste recovery in Italy, identifying environmental benefits despite high transport costs. Goli et al. (2020) developed a closed-loop model for perishable goods that integrates customer satisfaction and emission reductions using a hybrid whale-genetic algorithm. Kazancoglu et al. (2021) highlighted RL's environmental benefits in emerging economies through system dynamics modeling. Foroozesh et al. (2022) designed a green-resilient supply chain under uncertainty, incorporating risk, collaboration, and emissions using robust fuzzy programming. Al-Zubi et al. (2024) proposed closed-loop models for Jordan's citrus sector, integrating reverse logistics and waste valorization. Their approach reduced landfill waste by 37%, CO_2 emissions by up to 22%, and system costs by 17%.

The literature often treats forward logistics improvements and reverse logistics with waste valorization as separate research streams, limiting system-wide optimization. In PFSCs, where spatial and temporal dynamics and resource recovery are tightly linked, this fragmentation presents a clear gap. In response, this study introduces a spatially explicit agent-based framework that integrates forward logistics redesign, reverse logistics, and waste valorization. The framework simulates real-world actors such as farms, retailers, and collection points within a geographic space, enabling analysis of routing, zoning, and collection point decisions. It also incorporates waste valorization to convert unused produce into bio-compost and renewable energy, thereby supporting informed decision-making and enhancing the efficiency and circularity of PFSCs.

The remainder of the paper is structured as follows: Section 2 outlines the methodology, including the model structure and system design. Section 3 presents the results and discussion. Section 4 provides the conclusion along with directions for future research and discusses the implications of the proposed approach.

2 METHODOLOGY

To investigate the structural impacts of supply chain redesign, this study applies Agent-Based Modeling (ABM) to simulate and evaluate both the current and proposed configurations of the PFSC. ABM is particularly well-suited for this context because of its ability to capture decentralized decision-making and dynamic interactions among heterogeneous supply chain actors (Altarazi and Shqair 2023; Shqair et al. 2014; Shqair and Altarazi 2014; Macal and North 2010; Bonabeau 2002). Unlike other simulation approaches, ABM models the behavior of individual agents—such as farms, central markets (CMs), and retailers—and their interactions, which collectively shape system-wide outcomes. Its strength lies in handling non-linearities, uncertainty, and qualitative variables, making it an effective tool for exploring the complex, multi-echelon nature of PFSCs (van Dam et al. 2013). ABM also supports spatial and temporal modeling, enabling the integration of GIS data and realistic logistics layouts. This spatially explicit modeling approach has been used in previous studies to simulate perishable food logistics, manage urban freight systems, and analyze food supply chain disruptions (El Raoui et al. 2018; Nezami et al. 2023). Furthermore, the integration of ABM with GIS has proven effective for geospatial simulations in supply chains, highlighting its relevance for analyzing spatially distributed systems (Heppenstall et al. 2012; Castle and Crooks 2006).

To validate and demonstrate the practical utility of the proposed modeling framework, it was applied to a real-world case study of the Tomato Supply Chain (TSC) in Jordan. This case illustrates the typical challenges faced by PFSCs in developing regions, including fragmented production systems, inefficient logistics networks, and significant levels of food waste. Although the focus is on the tomato sector in Jordan, the framework is designed to be adaptable and transferable, making it applicable to a wide range of PFSCs in various geographical contexts.

2.1 Case Study Context

TSC in Jordan is fragmented, comprising mainly small-scale farmers who rent land seasonally and operate independently. Post-harvest, farmers transport tomatoes directly to CMs, as no centralized Collection Points (CPs) exist, leading to uncoordinated trips and increased costs and emissions (MoA 2023).

At CMs, tomatoes are sold per crate rather than by weight, sometimes below production cost, making the process unsustainable (MoA 2023). The lack of standardized grading and packing allows retailers to buy mixed-quality tomatoes in bulk, grade them independently, and redistribute them across Jordan based on socioeconomic segmentation. This practice creates pricing inequities, reduces transparency, and disadvantages farmers (MoA 2023). Retailers then deliver produce to their outlets nationwide.

Beyond logistical inefficiencies, the TSC also suffers from overproduction and food waste. With daily production between 900–1200 tons and a demand of 600 tons, around 400 tons are surplus. Of this, 80% is good quality, while 20% is considered below mid-grade standards (JFU 2023). Unsold tomatoes are often discarded weekly due to spoilage, highlighting the urgent need for structured waste management strategies.

Compounding these operational challenges are data-related uncertainties that hinder accurate supply chain analysis. The spatial distribution of tomato farms is highly variable, not only due to seasonal patterns but also because most farms are rented rather than permanently owned, resulting in shifting cultivation locations (MoA 2023). While regional production volumes are available, their allocation across individual farms remains unknown due to the absence of micro-level data. A similar challenge exists on the demand side: although aggregate demand is reported at the regional level, its disaggregation across individual retailers is undocumented and inherently probabilistic (MoA 2023). Together, these data gaps introduce considerable stochasticity and emphasize the need for a tailored modeling approach capable of capturing spatial heterogeneity and system-specific characteristics to support robust decision-making.

2.2 Synthetic Data Development

This study employs a synthetic data generation methodology originally developed by the authors in a previous publication (Sweis et al. 2024) to support the spatial and behavioral components of the Jordanian TSC. The methodology addresses the stochasticity, data scarcity, and structural fragmentation that characterize the TSC in Jordan, enabling the generation of high-resolution, context-specific input data.

The adopted methodology comprises: (1) zoning strategy development based on semi-structured interviews to delineate key tomato production areas; (2) farm location allocation using probabilistic distributions informed by regional farming patterns; (3) production volume assignment reflecting governorate-level agricultural statistics; (4) conversion of linear spatial logic into georeferenced coordinates using a custom-built JavaScript tool with the Google Maps API; and (5) creation of an integrated dataset capturing spatial, behavioral, and stochastic features suitable for simulation modeling (Sweis et al. 2024).

Retail demand nodes were derived from aggregated urban density and retail activity data to represent major consumption centers without relying on business-level information. The full methodology and technical details are available in Sweis et al. (2024).

2.3 Agent-Based Modeling of the Current Tomato Supply Chain

To simulate the current TSC in Jordan, an ABM was developed using AnyLogic 8.8.1 (University Edition). The model leverages GIS capabilities to incorporate spatial realism into the behavior of supply chain agents. Due to computational constraints, the simulation focused on Zone 1 and was designed to reflect realistic transportation and operational dynamics.

2.3.1 ABM Simulation Logic

Figure 1 provides a visual summary of the simulation logic, covering data imports, agent setup, weekly operations, and the replication process. The simulation begins with the import of the GIS map of Jordan, followed by the initialization of the replication counter and global performance metrics, including total farm distance (DF), total retailer distance (DR), cost incurred by farms (CF), cost incurred by retailers (CR), and transportation cost per ton (X). These values are reset at the start of each replication, and the simulation week counter (T) is initialized.

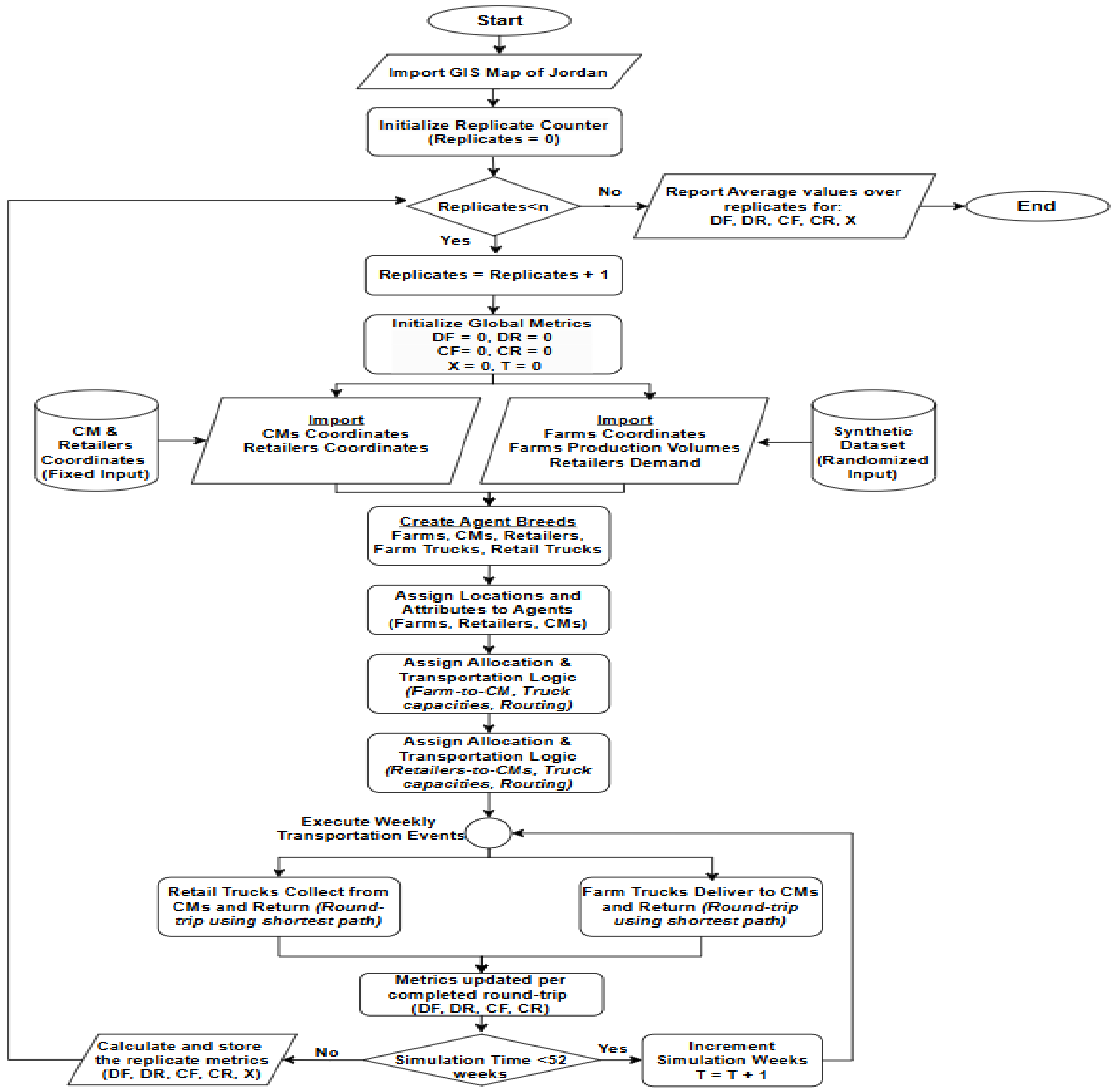

Figure 1: ABM simulation workflow for the current TSC.

Two datasets are imported: the first includes fixed geographic coordinates for CMs and retailers, while the second, derived from the synthetic dataset, contains randomized farm locations, production volumes, and retailer demand. These synthetic inputs are imported at the start of each replication to reflect real-world variability. Based on these inputs, agent breeds representing farms, CMs, retailers, and transport trucks are created.

Each agent in the model is assigned attributes that define its role and behavior in the simulation. These attributes include quantity-related parameters such as farm production levels, retailer demand, truck load capacity, and CM handling capacity, as well as geographic coordinates to establish each agent's spatial location. In addition, each agent has logistics-related properties, which include assigned pickup or delivery locations (e.g., which CM a farm delivers to, or a retailer collects from), routing logic (shortest-path algorithm), and operational assumptions such as round-trip movements and truck loading rules (full-load operation). These properties collectively determine how agents interact within the transportation and distribution system.

Each simulation week, farm trucks deliver produce to CMs and return, while retailer trucks collect produce from CMs and return to their retail locations. Both movements are modeled as round trips using the shortest-path algorithm. After each round trip, performance metrics are updated. This weekly cycle repeats until the simulation reaches 52 weeks. At that point, the model calculates and stores the average metrics for the entire replication. This process is repeated for a predefined number of replicates to ensure statistical reliability, and the model then reports the average performance metrics across all replications.

As illustrated in Figure 2, the screenshot of the current TSC agent-based model shows the spatial configuration and truck movements under the existing centralized setup. Part (a) displays farm trucks departing from various farms within Zone 1 and delivering produce to the Irbid central market. Part (b) shows retailer trucks collecting produce from Amman and Zarqa CMs and returning to their respective retail locations.

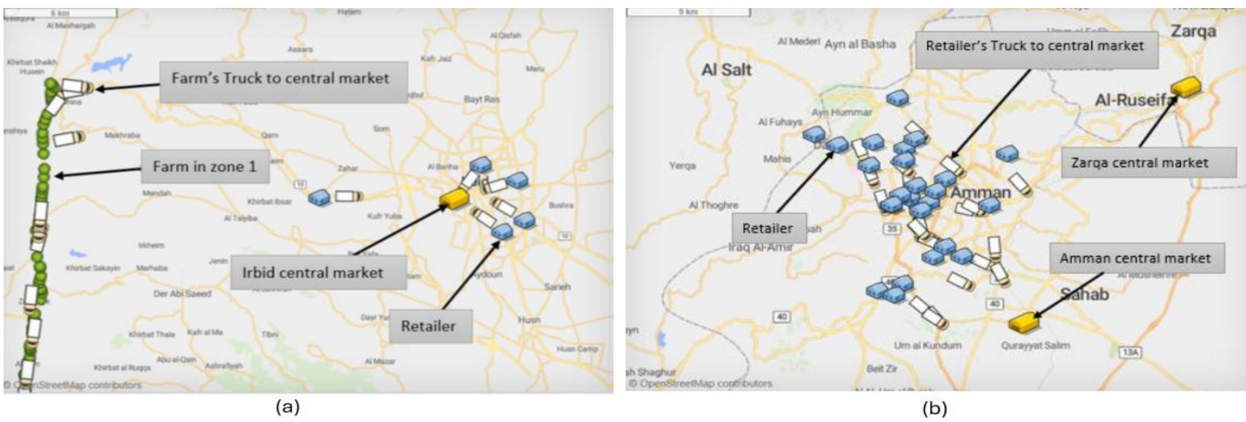

Figure 2: Screenshot of the current TSC ABM: (a) farm truck routes to Irbid CM; (b) retailer truck routes to Amman and Zarqa CMs.

2.3.2 ABM Assumptions

The agent-based model was developed based on the following assumptions, each grounded in available data or standard logistics practices to ensure realism and manageability:

- Only 75% of tomato produce is transported to CMs, as 25% is unfit for commercial sale due to mechanical damage or over-ripeness. This loss rate is based on estimates from the Jordanian Ministry of Agriculture (MoA 2023).
- 20% of tomatoes received at the CMs are not shipped to retailers, due to surplus volumes, spoilage, or further mechanical damage. This assumption is also based on estimates obtained from the from the Jordanian Ministry of Agriculture (MoA 2023).
- All trucks operate at full load. This reflects a common logistics assumption intended to minimize transportation cost per trip and improve operational efficiency.
- Farm and retailer trucks have a uniform capacity of 2 tons. This value is based on vehicle sizes commonly used for agricultural transport in Jordan (JFU 2023).
- Truck fuel efficiency is 4 km/L of diesel. This is consistent with performance benchmarks for light-duty diesel trucks in Jordan, as cited in OpenAI (2023).

- The price of diesel is 0.8 JOD/L. This reflects average fuel prices during the modeling period, based on OpenAI (2023) and publicly available energy reports.
- Routing logic is based on the shortest path between origin and destination. This is implemented using AnyLogic's GIS engine with real-road networks and was validated through comparison with Google Maps routes.
- Truck availability is assumed to be non-limiting. This simplifies the analysis by focusing on transportation flows and cost performance rather than fleet scheduling constraints.
- Both farm production and retailer demand are uniformly distributed over weekly time intervals. This was necessary due to data availability being limited to annual aggregates. Distributing these values evenly across 52 weeks ensures consistent weekly quantities and avoids introducing artificial seasonal fluctuations. This temporal aggregation does not affect the accuracy of the model, as the evaluation focuses on transportation performance metrics such as total distance travel and cost. Moreover, using weekly aggregates reduces potential errors introduced by the full truckload assumption, which would be more sensitive under daily-level variability.

Although the simulation model incorporates several simplifying assumptions to manage complexity and data limitations, their effects are mitigated by applying them consistently across both the current and proposed scenarios. Since both models are governed by the same structural and temporal assumptions, comparative analysis remains valid. This approach is particularly important given the high level of complexity and uncertainty inherent in real-world supply chains like TSC. By maintaining consistent assumptions, the model ensures that any observed differences in performance metrics are attributable to the proposed structure rather than modeling artifacts.

2.3.3 ABM Verification and Validation

Model verification involved inspecting agent behavior logic, including statechart transitions and transport operations. All imported datasets were checked for consistency, and commands related to truck movements and distance tracking were confirmed to function as intended.

For validation, selected truck trips were manually compared to Google Maps distances. Results showed that relative errors remained below 1%, confirming the accuracy of the GIS-based routing in AnyLogic. For instance, the route of Truck 3 from Farm 3 to Irbid CM yielded a simulated one-way distance of 25.528 km, closely matching Google Maps' value of 25.5 km, with only a 0.1% relative error.

2.3.4 Replication and Sensitivity Analysis

To ensure statistical reliability, a pilot study of 10 simulation runs was conducted. Based on a standard deviation of 0.259 JOD/ton in transportation cost, a 90% confidence level, and a margin of error of 0.15 JOD/ton, the estimated number of required replications was approximately 9. Since 10 runs were already completed during the pilot phase, no additional replications were needed.

In addition to estimating the required number of replications, the same 10 simulation runs were analyzed as a sensitivity study to evaluate the effect of input variability on model outputs. Each run used independently generated synthetic data for Farm Coordinates, Farms Production Volumes, and Retailers Demand—representing the three main sources of stochasticity in the system. The resulting transportation cost per ton had a mean of 18.5 JOD and a standard deviation of 0.259 JOD, corresponding to a coefficient of variation (CV) of approximately 1.4%. This low CV value indicates that model outputs remained stable under input uncertainty, supporting the robustness of the framework.

2.4 Proposed Framework: Integrating Forward Network Redesign, Reverse Logistics, and Waste Valorization

To overcome inefficiencies in the current TSC—such as long farm-to-CM transportation distances and high produce waste—a redesigned logistics framework was developed. This model introduces intermediary nodes and reorganizes produce flow through strategically placed CPs and regional hubs to enhance efficiency and sustainability.

CPs serve as local aggregation points for geographically clustered farms. They were positioned at 2-kilometer intervals along Route 65, the main agricultural corridor, to reduce farm-level travel, align with road infrastructure, and improve routing efficiency. Farms are assigned to the nearest active CP while respecting CP capacity limits. From there, tomatoes are transported to regional hubs that act as centralized units for sorting, grading, and dispatching to retailers.

Each agricultural zone was assigned one regional hub to serve as a central unit for sorting, grading, and distribution. To ensure efficient placement, the hub's location was determined using a Center of Gravity (CoG) method that accounts for both upstream supply from CPs and downstream demand from retailers. This spatially balanced positioning minimizes transportation distances and enhances routing efficiency within each zone. Each hub is equipped with a biogas unit to process organic tomato waste from three distinct sources: low-quality produce delivered from farms via CPs, unsold or prematurely ripened tomatoes accumulated at the hub, and excess or damaged tomatoes returned from retailers using reverse logistics. This reverse flow utilizes the backhaul of retailer trucks, avoiding additional transportation costs. The collected organic waste is then valorized into renewable energy and compost through biogas processing, ensuring complete recovery of tomato waste streams.

This redesign transforms the supply chain from a linear to a closed-loop model, supporting waste recovery and aligning with circular economy principles. Figure 3 compares the current and proposed TSC frameworks, highlighting the addition of CPs, regional hubs, reverse logistics, and biogas-based waste processing.

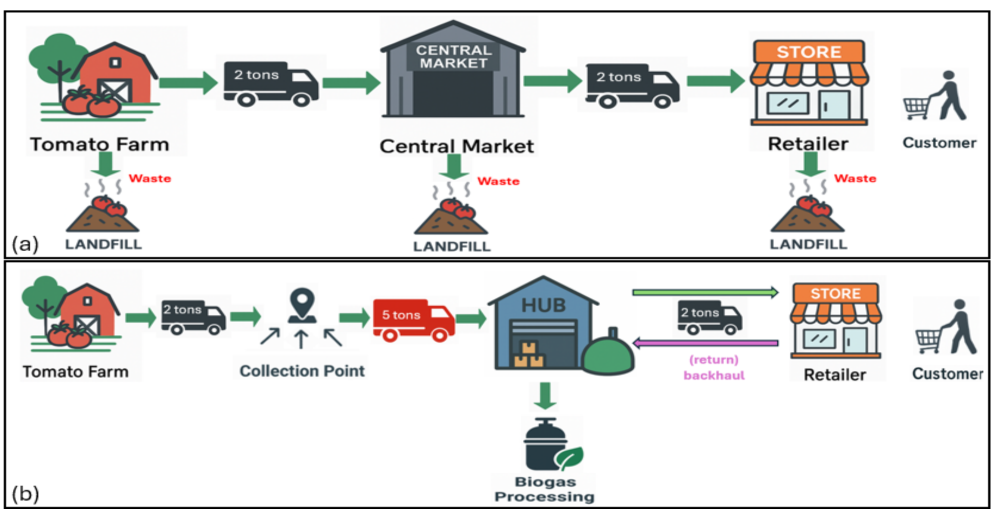

Figure 3: Comparison of the current and proposed TSC frameworks: (a) centralized model with high waste and no recovery; (b) decentralized model with CPs, hubs, reverse logistics, and biogas processing.

2.5 Agent-Based Evaluation of the Proposed Framework

To model the redesigned supply chain, the current ABM described in Section 2.3 was modified to reflect the new structure. New agent roles and interactions were defined to represent farms, CPs, regional hubs, and retailers. A summary of these agents, their decision-making behaviors, and the input data used to drive their simulation logic is presented in Table 1. The model simulates three main forward flows: farms deliver tomatoes to nearby CPs using 2-ton trucks; CPs consolidate and forward the produce to regional hubs using 5-ton trucks; and at the hubs, tomatoes are graded before being collected by retailers. Reverse logistics are also incorporated, where retailers return unsold or damaged tomatoes to the hub using the same trucks on their return trips. Figure 4 is a screenshot of the proposed ABM interface, showing (a) the forward logistics flow from farms to CPs and from CPs to the regional hub, and (b) the reverse logistics flow from retailers back to the hub via backhaul.

Table 1: Summary of Agent Behaviors and Input Data in the Proposed ABM.

Agent	Decision Making & Behavior	Input Data
Farm	Each farm is assigned to a CP using zonal clustering logic, where farms within the same sub-region are grouped and linked to a designated active CP. Farms produce a fixed weekly volume and dispatch to CPs using 2-ton trucks.	Farm spatial coordinates and weekly production volumes (synthetic data generated as in Sweis et al., 2024)
Collection Point	Receives tomatoes from farms over the week and dispatches accumulated volumes to the regional hub at the end of each week using 5-ton trucks.	CP location and capacity, assigned service areas, dispatch schedule.
Regional Hub	Applies quality grading (A–D) to incoming tomatoes. Grades A and B are recorded for distribution to retailers. Grades C and D are retained at the hub for recycling purposes.	Grading thresholds and proportions; hub location; synthetic quality distribution.
Retailer	Collects tomatoes weekly from the hub based on synthetic demand. Returns unsold/damaged tomatoes to the hub using the same vehicle (backhaul).	Retailer spatial coordinates, synthetic weekly demand, average return rate.
Truck	Simulates round-trip transport using fixed capacities (2-ton for farm–CP, 5-ton for CP–hub, and retailer-owned vehicle for retailer–hub -retailer trips). Agents move along the shortest path on a GIS map.	GIS coordinates for agent locations, vehicle capacities, dispatch schedule.

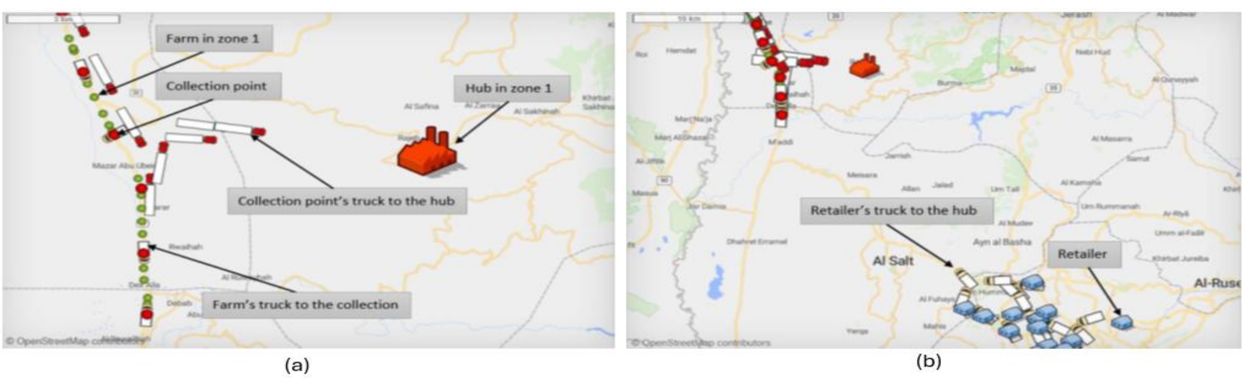

Figure 4: Screenshot of the proposed ABM: (a) forward flow from farms to CPs and from CPs to hub; (b) reverse flow from retailers to hub via backhaul.

3 RESULTS AND DISCUSSION

This section presents a comparative analysis of the current and proposed TSC configurations based on simulation results for Zone 1. Key performance metrics—namely annual transportation distance, annual transportation cost, and transportation cost per ton—were evaluated to assess the effectiveness of the redesigned logistics framework.

As illustrated in Figure 5(a), the annual transportation distance in the current scenario for Zone 1 is 8,718,247 km. Under the proposed framework, this distance is reduced to 6,008,080 km, representing a 31.1% decrease. This reduction is mainly driven by the introduction of CPs, which aggregate produce from nearby farms, and regional hubs, which minimize redundant travel.

Figure 5(b) compares the annual transportation cost between the current and proposed configurations. In the baseline scenario, the total transportation cost is 1,743,649 JOD. This cost drops to 1,201,616 JOD under the proposed framework, yielding 31.1% savings. This improvement is attributed to both the optimized CP-hub structure and the reduction in long-distance farm-to-central market trips.

The impact of the redesigned logistics system is even more evident when examining the transportation cost per ton, shown in Figure 5(c). The cost per ton is reduced from 18.5 to 11.9 JOD, a 35.9% reduction. This improvement is enabled by the integration of reverse logistics through retailer backhaul trips, which utilize return vehicle capacity to transport unsold or damaged tomatoes from retailers to hubs for processing.

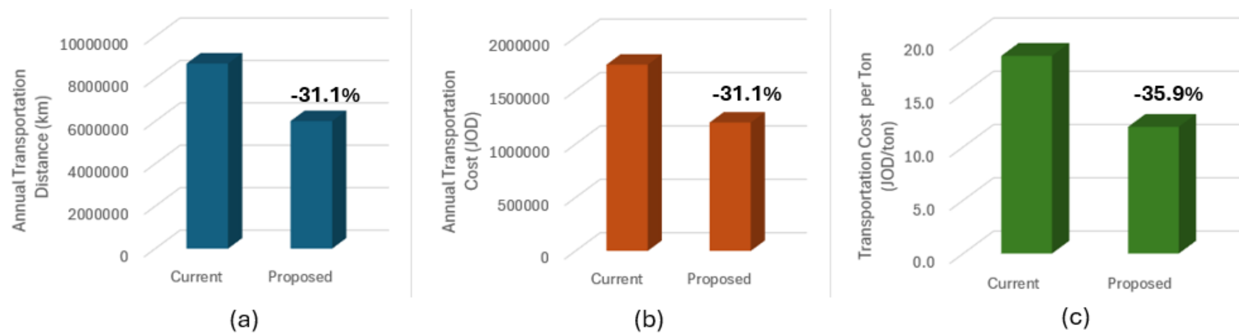

Figure 5: Performance comparison between the current scenario and proposed framework-Zone 1: (a) Annual Transportation Distance, (b) Annual Transportation Cost, and (c) Transportation Cost per Ton.

Figure 6 presents the transportation cost distribution by transportation leg in the current scenario and proposed framework. In the current scenario (Figure 6a), the farm-to-CM leg accounts for 85.5% of the total cost, highlighting the heavy burden placed on farmers. The remaining 14.5% corresponds to retailer-to-CM transport.

Under the proposed framework (Figure 6b), the distribution of transportation costs becomes more balanced. The farm-to-hub segment—which includes transport from farms to CPs (3.4%) and then to hubs (30.1%)—accounts for 33.5% of the total cost, representing less than half of the farmer's share in the current scenario. In contrast, the retailer-to-hub leg constitutes 66.5%. This redistribution leads to a more equitable benefit-to-cost ratio across the supply chain. Given that retailers typically capture a larger share of the profit margin compared to farmers, it is more reasonable for them to bear a greater portion of the transportation burden. This shift promotes a fairer and more sustainable allocation of logistical responsibilities. In addition to these quantitative improvements, the redesigned framework introduces several structural and operational changes that enhance overall system sustainability. Table 2 summarizes these key differences, providing a holistic comparison between the current and proposed tomato supply chain scenarios.

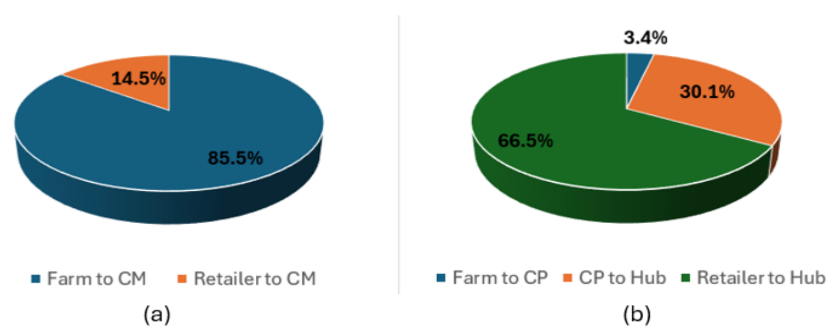

Figure 6: Transportation cost distribution by leg in Zone 1: (a) current scenario, (b) proposed framework

Table 2: Structural and Logistical Comparison of the Current vs. Proposed TSC Scenarios.

Aspect	Current TSC	Proposed TSC
Network design	Farm → CM → Retailer	Farm → CP → Hub ⇄ Retailer
Intermediary facilities	CMs	CPs and regional hubs
Waste handling	None	Biogas & compost processing at hub
Reverse logistics	None	Included (backhaul from retailer to hub)
Sustainability features	None	Circular model with waste valorization
Routing logic	Farms assigned to nearest CM; shortest paths	Farms assigned to nearest CPs; CoG-based hub placement; shortest paths
Average transportation cost/ton	18.5 JOD	11.9 JOD (↓35.9%)
Cost distribution	Farms cover 85.5% (to CM), retailers 14.5%	Farms cover 33.5% (to hub), retailers 66.5%

While the simulation results reflect significant performance improvements, they are grounded in a separate techno-economic feasibility study that defines stakeholder responsibilities and cost-sharing arrangements. Informed by this analysis, the model assumes that farmers handle transport to collection points and hubs, while retailers manage reverse logistics via backhaul trips. Returned tomato waste is processed into compost and biogas at the hubs, with profits partially shared with retailers to promote participation. As this feasibility study lies beyond the scope of the current manuscript, its full findings will be presented in a separate publication.

4 CONCLUSION, IMPLICATIONS, AND FUTURE WORK

This study presents an agent-based modeling framework that integrates forward logistics redesign, reverse logistics, and waste valorization to improve the sustainability and efficiency of perishable food supply chains. Through the case of the tomato supply chain in Jordan, the research demonstrated the value of transitioning from a centralized, linear market system to a decentralized, closed-loop configuration featuring collection points, regional hubs, and biogas units.

Simulation results revealed notable performance improvements under the proposed framework, including a 31.1% reduction in total transportation distance and cost, and a 35.9% decrease in transportation cost per ton. These gains were primarily driven by enhanced spatial aggregation at collection points, the strategic placement of hubs, and the efficient use of vehicle backhauls through reverse logistics. In addition to cost savings, the transportation distance reduction contributes to lowering the carbon dioxide footprint of the supply chain and enables complete recovery of tomato waste streams, thereby supporting broader environmental sustainability goals

The findings hold important implications for policymakers, supply chain planners, and sustainability advocates, particularly in developing regions where perishable food systems are often constrained by limited data, fragmented infrastructure, and environmental vulnerability. While the case study focused on tomatoes, the proposed framework is inherently scalable and adaptable, offering a robust blueprint for optimizing a wide range of PFSCs. Its modular structure allows customization based on commodity-specific characteristics such as perishability, value, and waste recovery potential. By integrating forward logistics redesign, reverse flows, and valorization, the framework enables a shift from reactive waste management to proactive resource recovery, fostering more resilient, equitable, and sustainable food supply chains.

For future work, expanding the framework to other agricultural zones and perishable commodities represents a promising direction. This study focused on Zone 1 as a pilot application of the framework due to the complexity of the model, computational load, and scope constraints. While Zone 1 provided sufficient realism to validate the framework under spatial and operational variability, applying the model to additional zones with different densities and topologies is a valuable direction for future research. Additional research could also explore the integration of real-time sensing and IoT-based monitoring to enable adaptive logistics and predictive waste management, thereby advancing the role of digital twins in sustainable agri-food systems. Moreover, coupling the agent-based model with a system dynamics component may offer deeper insight into the interactions between waste generation and biogas production rates. These enhancements would further reinforce the model's potential to support decision-making across multiple tiers of PFSCs.

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